ANNUAL PROGRESS REPORT

1999 - 2000

INVESTIGATION OF A NEW CLASS OF LOW-PROFILE MULTI-LAYER PRINTED ANTENNAS

PRINCIPAL INVESTIGATOR:
AHMAD HOORFAR, Ph.D.

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

DEPARTMENT OF ELECTRICAL AND
COMPUTER ENGINEERING
VILLANOVA UNIVERSITY
VILLANOVA, PA 19085

PREPARED FOR:

OFFICE OF NAVAL RESEARCH
ARLINGTON, VA 22217

OCTOBER, 2000

TABLE OF CONTENTS

I. SUMMARY

This progress report summarizes our research efforts on modeling, analyses and optimization of multi-layered printed antennas for various applications in communications and radar that may require high gain, wide bandwidth, multi-band and/or circular polarization. The report covers the time-period, October 1999 – September 2000. The technical progress made during this period include:

i) The Yagi-like high gain concept has been extended to the practical cases of microstrip-fed, proximity-fed and aperture-fed array of rectangular patches. The analysis and optimization of each structure is performed using our electromagnetic optimization engine which can globally optimize multiply stacked multiple patches of arbitrary shapes. For each case a 3-layer Yagi-like antenna is optimally designed at a frequency of 10 GHz. Performance of each antenna in terms of its gain, return loss and input impedance versus frequency is investigated. It shown that a gain of about 12 dBi or higher can be obtained in each feeding scheme. In addition, for each case we have investigated the coupling effects between two or more these Yagi-like sub-arrays in order to assess their performance in a linear array application. The results for the gain degradation clearly show that to fully take advantage of the Yagi-like gain enhancement technique, one should globally optimize gain of the whole array, in the presence of the mutual coupling effects, rather than an element in isolation. Examples of such global optimization as applied to linear arrays of Yagi-like elements of printed narrow strips are presented.

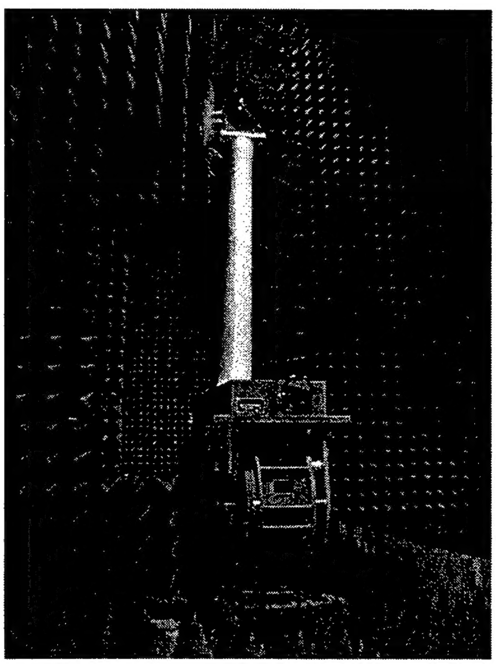
ii) A gain enhancement method under investigation in this project has been based on the resonance condition of a single microstrip patch in a multilayer geometry with a high permittivity focusing superstrate layer. We had previously demonstrated the feasibility of the method in design of a circularly polarized probe-fed microstrip antenna. Coaxial feeding technique, however, is not suitable for printed array applications. We have now extended this high gain technique to design of proximity-fed and aperture-fed antennas for applications that require linear, circular or dual polarization (i.e., polarization diversity antennas). It is important to note that the total thickness of the structures analyzed here may be impractical for lower microwave frequency ranges. Extension of the concepts into millimeter-wave region, however, is straight forward, and should result in low profile high gain radiating elements that would be attractive for many wireless applications such as in Local Multi-point Distribution System (LMDS) that operates at 27 GHz and higher.

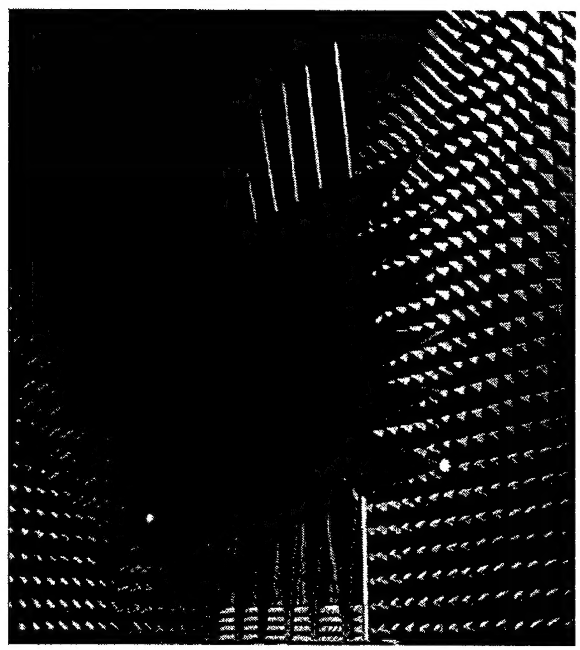
iii) We have extended our method of moment code to include Yagi-like stacked patch antennas printed in a multi-layer anisotropic medium. Integration of this code with our evolutionary

optimization engine is currently in progress. Upon completion the optimization engine will be used to investigate these antennas for high gain multi-beam applications.

iv) We are currently in the midst of developing a numerical code, based on the finite-difference time-domain (FDTD) method, for analysis of the multi-layer microstrip antennas on cylindrical surfaces. Upon completion, this code will be used for radiation as well as RCS analysis of the Yagi-like antennas printed in a curved multi-layered dielectric medium.

v) The measurement facility of the Antenna Research Laboratory (ARL), which has been partially funded by the present grant, is now completed and will be operational in November 2000. This state-of-the art indoor facility includes a 29' x 27' x 28' anechoic chamber (compact range) capable of fully automated high quality pattern and gain measurements from 1-40 GHz. In the coming year we plan to use this range to fabricate and test some of the high gain design concepts developed during the course of this project. In addition we have teamed with Naval Sea Systems Command, NAVSEA-Philadelphia, to extend the capabilities of ARL to 100 GHz and include accurate radar cross section (RCS) measurements. This Academia/Government relationship allows Villanova's ARL to offer extensive facilities and expertise to Government and Industry for the development, integration, evaluation and testing of RCS and antenna components and systems.





Compact Range Anechoic Chamber at Villanova University.

II. PUBLICATIONS

In the last two years, this research project has resulted in the following journal and conference papers:

1. A. Hoorfar, "Analysis of a 'Yagi-like' printed stacked dipole array for high gain applications," *Microwave and Optical Technology Letters*_, Vol 17, No. 5, pp. 317-321, April 1998.

2. A. Hoorfar, "A 'Yagi-like' gain enhancement method for multi-layer printed antennas," Proceedings of the *1998 International Symposium on Electromagnetic Theory*, PP. 250-252, May 1998, Thessaloniki, Greece.

3. A. Hoorfar and D. C. Chang,"Semi-analytical solutions for microstrip Green's functions in multi-layered media," Proceedings of the *1998 International Symposium Electromagnetic Theory*, PP. 618-620, May 1998, Thessaloniki, Greece.

4. K. Chellapilla and A. Hoorfar, "Evolutionary programming: an efficient alternative to genetic algorithms for electromagnetic optimization problems," Proceedings of the *IEEE AP-S International Symposium*, Atlanta, GA, pp. 42-45 , June 1998.

5. A. Hoorfar and K. Chellapilla, "Gain optimization of a multi-layer printed dipole array using evolutionary programming," Proceedings of the *IEEE AP-S International Symposium*, Atlanta, GA, pp. 46-49 , June 1998.

6. A. Hoorfar, "Integral equation modeling of microstrip circuits and antennas using closed-form Green's Functions," *Microwave and Optical Technology Letters*, Vol. 20, Number 5, pp.342-345, March 1999.

7. A. Hoorfar, G. Girard and A. Perrotta, "A dual frequency circular-polarized electromagnetically-fed microstrip antenna,' *Electronics Letters*. Vol. 35, Number 10, pp.759-761, May 1999.

8. A. Hoorfar, "Mutation-based evolutionary algorithms and their applications to optimization of antennas in layered media," Proceedings of the *IEEE AP-S International Symposium*, Orlando, FL, pp. 2876-2879, July 1999.

9. R. G. Holland and A. Hoorfar, "Gain enhancement method for microstrip antennas in uniaxial anisotropic media," *Digest of the 26th General Assembly of the International Union of Radio Science (URSI)*, Toronto, Canada, August 1999.

10. K. Chellapilla and A. Hoorfar, "Intelligent operator design in evolutionary computation and its application to antenna optimization problems," *Digest of the 26th General Assembly of the International Union of Radio Science (URSI)*, Toronto, Canada, August 1999.

11. A. Hoorfar and Yuan Liu, "A study of Cauchy and Gaussian mutation operators in evolutionary programming optimization of antenna structures," Proceedings of the *16th Annual Applied Computational Electromagnetics Conference*, Monterey, CA, pp. 63-69, March 2000.

12 Yuan Liu and A. Hoorfar, "Optimization of antenna arrays using evolutionary programming", Proceedings of the *2000 IEEE Sarnoff Symposium*, Ewing, NJ, pp. 147-150, March 2000.

13 C. Wan and A. Hoorfar, "Improved Design Equations for Multilayer Microstrip Lines," *IEEE Microwave and Guided Wave Letters*,, Vol. 10, Number 6, pp. 223-24, June 2000..

14 A. Hoorfar and Yuan Liu, "Antenna Optimization Using an Evolutionary Programming Algorithm with a Hybrid Mutation Operator," Proceedings of the *IEEE AP-S International Symposium*, Salt Lake City, UT, pp. 1026-1029, July 2000.

III. PERFORMANCE OF YAGI-LIKE ARRAY OF STACKED PATCH ELEMNTS WITH VARIOUS FEEDING TECHNIQUES

In our last two annual technical reports [1,2] we presented the analysis and gain optimization of a microstrip Yagi-like antenna which consists of a reflector (ground-plane), a driver and a finite number of embedded director strip elements. We also discussed the performance of these structures when they are used as radiating elements in an array environment. The structure previously analyzed, however, was difficult to realize in practice because it was assumed made of narrow strip dipoles, fed by a delta-function voltage generator. We have now extended the analysis and optimization to practical cases of microstrip-fed, proximity-fed and aperture-fed Yagi-like array of rectangular patches. In addition, in each case we have investigated the coupling effects between two or more Yagi-like sub-arrays in order to assess their performance in a linear array application. The analysis and optimization of each structure is performed using our electromagnetic optimization engine which can globally optimize multiply stacked multiple patches of arbitrary shapes. This numerical engine is based on a hybrid combination of Method of Moments (MOM) and Evolutionary Programming (EP)[3].

In gain optimizations of the direct microstrip-line fed (Figure 1) and the proximity-fed (Figure 2) Yagi-like array of stacked rectangular patch elements described in the following sections, we first represented the structure by a column vector,

$$\overline{X} = [L_1, L_2, ..., L_N; W_1, W_2, ..., W_N; W_f, S_f; \varepsilon_{r1}, \varepsilon_{r2}, ..., \varepsilon_{r1}; d_1, d_2, ..., d_N]^T \tag{1}$$

where L_1, W_1, ε_{ri} and $d(i)$ are length of the patch, width of the patch, dielectric constant and thickness of the i-th dielectric layer, respectively.; W_f and S_f are the width and the inset of the microstrip feed-line (for the proximity-fed case), respectively. To optimize the parameters in (1) a fitness function was constructed as,

$$F(\overline{x}) = -\ G(\theta,\phi;\overline{x}) + \sum_{m=1}^{M} V(f_m,\overline{x}) + Q\sum_{m=1}^{M} \left|V_{max} - V(f_m,\overline{x})\right|^2 P_v(i)$$

$$P_v(m) = \begin{cases} 1 \ , \ V(f_m,\overline{x}) \geq \ V_{max} \\ 0 \ , \ V(f_m,\overline{x}) < \ V_{max} \end{cases} \tag{2}$$

Where G is the power gain in (θ, ϕ) direction obtained from the moment method solution of a mixed potential integral equation with rooftop basis functions; V and V_{max} are the VSWR of the structure, evaluated at frequency f_m , and the maximum allowed VSWR within the frequency band

of f_M-f_1, respectively. Q is a constant set to a value of larger than 10. We note that the summations in (2) guarantee, in the desired frequency range, an optimized solution that is matched to the feed line with a given characteristic impedance.

A. Yagi-like Antenna Directly Fed by Microstrip Line

To demonstrate the feasibilty of Yagi-like stacked microstrip patch array with a direct microstrip line feeding we consider the case of a 3 layer structure shown in Figure 1.

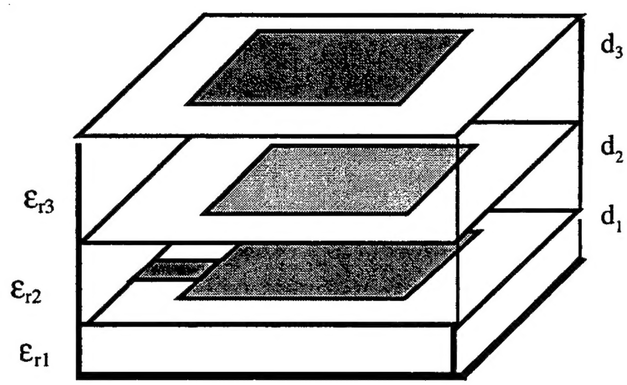


Figure 1: Multi-layer Yagi-like stacked patch array

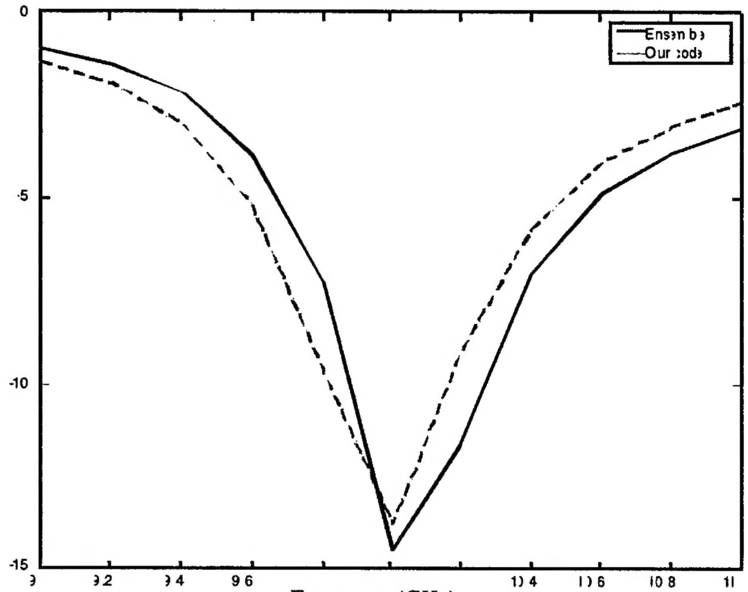
Assuming Duroid dielectric layers with $\varepsilon_{r1}= \varepsilon_{r2}= \varepsilon_{r3}=2.2$, the structure was optimized subject to the constraint of VSWR< 2. Since the widths of the three patches are not the key parameters that affect the gain, we fixed each width according to the width of a microstrip patch that leads to good a radiation efficiency [4]:

$$W=\frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}}=\frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{3}$$

Where v_0 and f_0 are the free-space velocity of light and the resonant frequency, respectively; ε_o , μ_o ε_r, are the permittivity and permittivity of the free-space, and the dielectric constant of the substrate, respectively. In addition the thickness of the first layer is set to a practical value of 1.5875 mm. The optimization parameters in this case were, thus, lengths of the three patches, which were allowed to vary in the range of [0.25, 0.65] λ_d , and thickness of layer 2 and layer 3 which were allowed to vary in the range of [0.1, 0.5] λ_d, where λ_d is the wavelength in dielectric. The fitness function in (2) was then minimized with the EP parameters of μ =10 and q=4 where μ and q are the population size and the number of opponents in the tournament selection respectively. Gain of more than 11.3 dBi was obtained within 125 generations. The optimized parameters are given in table 1. Figures 2 and 3 show the return loss, S_{11}, and gain of the optimized structure versus frequency.

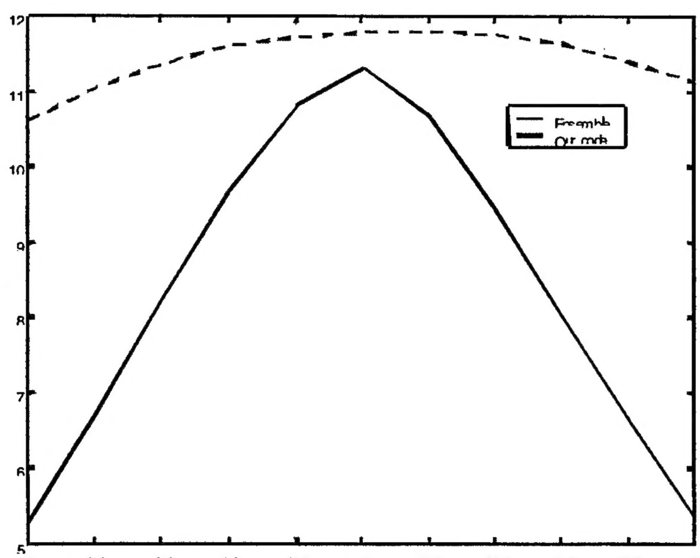
Table 1: Optimized 3-layer stacked patch array

	Thickness (λ_d)		Length of Patch (λ_d)			Fitness Value
Parameters	d_2	d_3	L_1	L_2	L_3	Gain (dBi)
Optimized Value	0.4353	0.199	0.4012	0.363	0.200	11.338



Frequency (GHz)

Figure 2: |S11| as a function of frequency; the dash-line is the results obtained from Ensemble



Frequency (GHz)

Figure 3: Optimized gain as a function of frequency; the dash-line is the results obtained from Ensemble

In order to verify the high performance of this optimized structure, the results obtained from the commercial simulator, Ensemble [5] are also included for comparison. Discrepancy in the gain plots is because the Ensemble results are plotted for the 'matched-gain' which ignores the input mismatch losses. These figures clearly show that a high gain together with a good match is achieved at the optimized frequency of 10 GHz.

B. Yagi-like Antenna Proximity-fed by Microstrip Line

In the previous case, the microstrip line directly fed the multi-layer antenna. We now present the feasibility of proximity-coupled method to feed the Yagi-like stacked patch structure. Proximity-coupled feeding has many advantages over direct microstrip-line feeding [6]: lower level of spurious radiation, wider bandwidth and greater flexibility in impedance matching especially in an array environment. An example of the proximity-fed Yagi-like configuration is shown in Figure 4.

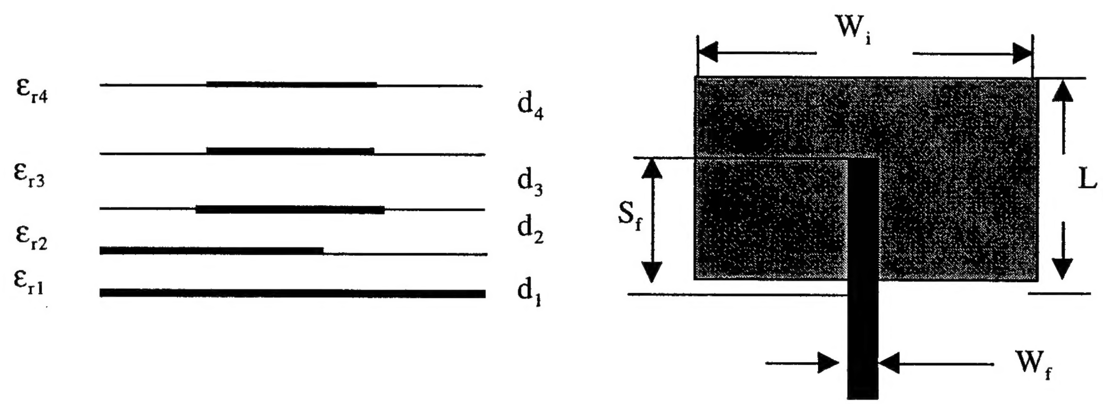


Figure 4: Yagi-like stacked microstrip patches proximity-fed by a microstrip-line

where a microstrip line in the first layer electromagnetically feeds the driver patch on top of the second layer while two director patch elements are located in layers 3 and 4. In gain optimization of this structure using EP, the dielectric constants were set fixed to ε_{ri}=2.2, i=1,2,3,4 and $d_1 = d_2 =$ 0.9735 mm. The length, and widths of each patch, the thickness, d_3 and d_4, of the dielectric layers and the width W_f and the inset length S_f of the microstrip-line were then optimized to provide a 50 ohm match at f=10 GHz with a maximum VSWR of V_{max}= 1.5. A broadside gain of more than 12.5 dBi was achieved within 200 generations. The final optimized parameters are shown in Table 2. The plots of S_{11} and gain as a function of frequency for the optimized structure are shown in Figure 5. The corresponding plots for the input impedance of the antenna as a function of frequency, together with results obtained from Ensemble are shown in Figure 6.

Table 2. Optimized proximity fed Yagi-like array for maximum gain

	Thickness (λ_d)		Length of patch (λ_0)			Width of patch (λ_0)			Feed (λ_0)		Fitness
Parameters	d_3	d_4	L_1	L_2	L_3	W_1	W_2	W_3	W_f	S_f	Gain (dBi)
Optimized Values	0.437	0.726	0.267	0.277	0.204	0.494	0.498	0.451	0.078	0.114	12.58

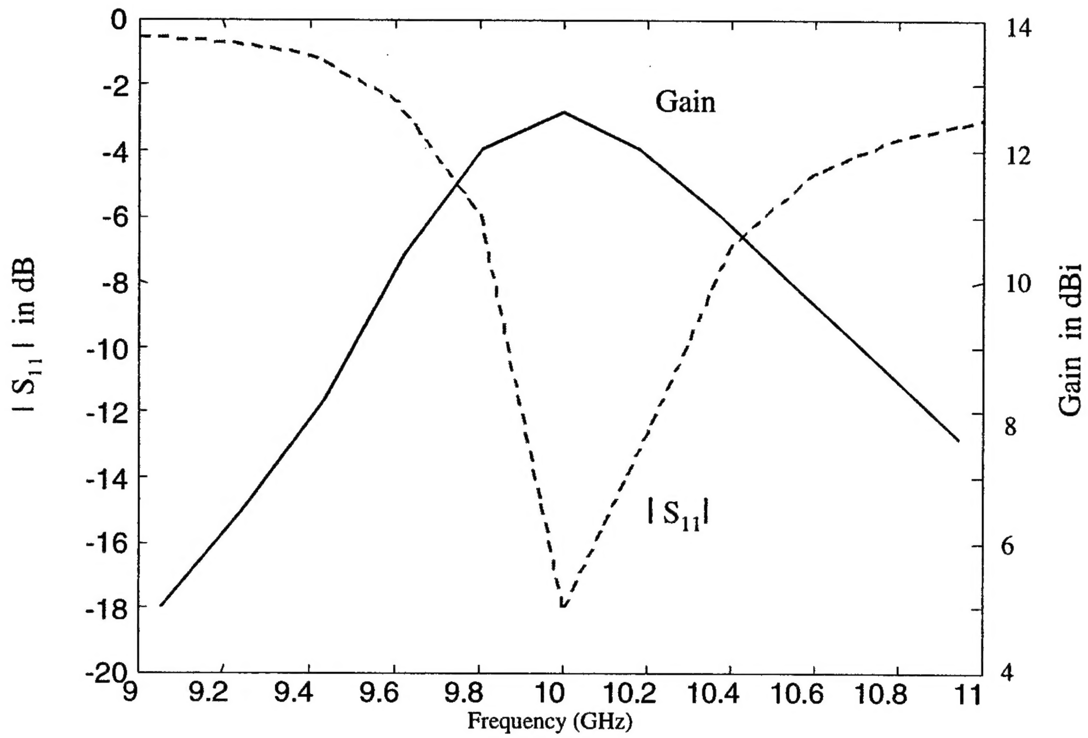


Fig. 5

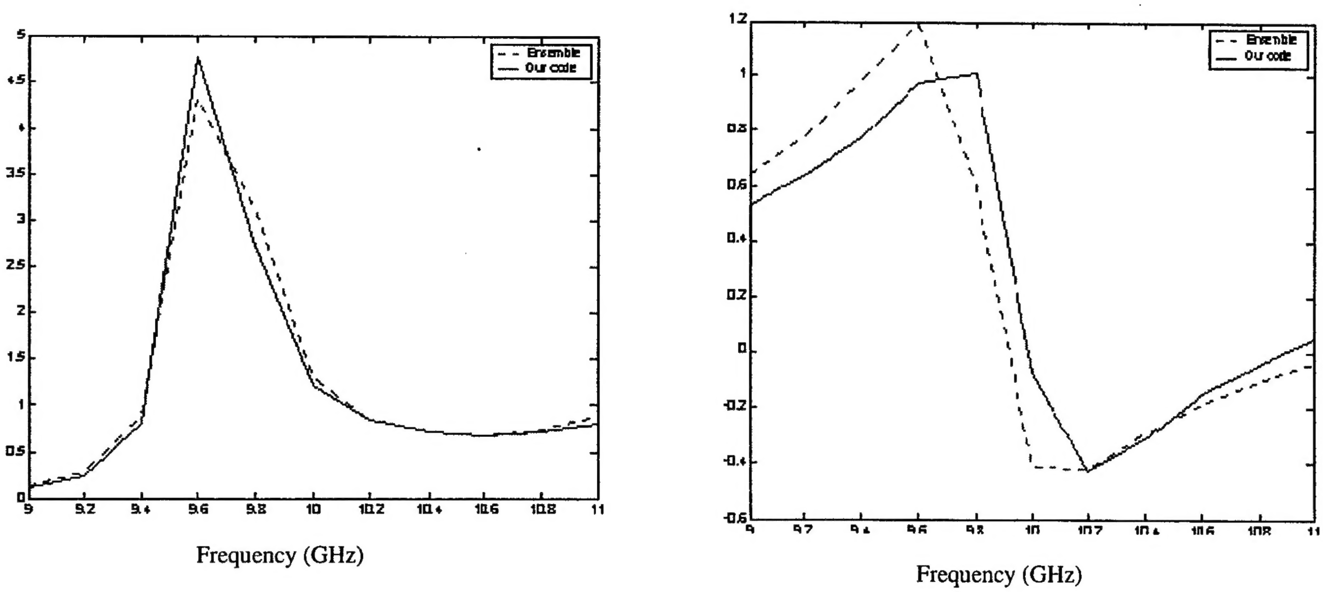


Fig. 6: Input resistance (left) and input reactance vs frequency; Ensemble results are shown in dashed-line.

C. Yagi-like Antenna Aperture-fed by Microstrip Line

Aperture-coupling has proven to be a reliable and a robust feeding technique of microstrip antennas [7, 8]. The lack of galvanic contacts makes it a preferable way to realize the feeding of large printed antenna arrays. We have investigated the feasibility of combining the aperture feeding technique with the Yagi-like gain enhancement technique for the stacked rectangular patches discussed in subsections A and B, above. Based on the optimized proximity-fed structure in subsection B, we succeeded in design of an aperture fed high gain Yagi-like antenna. The antenna is composed of four layers as shown in Figure 7: the feed-line substrate (ε_{r1}=2.2, d_1=0.037λ_{d1}) and three supporting dielectric layers (ε_{r2}= ε_{r3}= ε_{r4}=2.2, d_2=0.037λ_{d2}, d_3=0.437λ_{d3}, d_4=0.726λ_{d4}). A rectangular slot is placed on the ground plane. The feeding line is placed at the center of the slot. The whole structure is therefore symmetric. Starting with the optimized parameters in Table 2, a

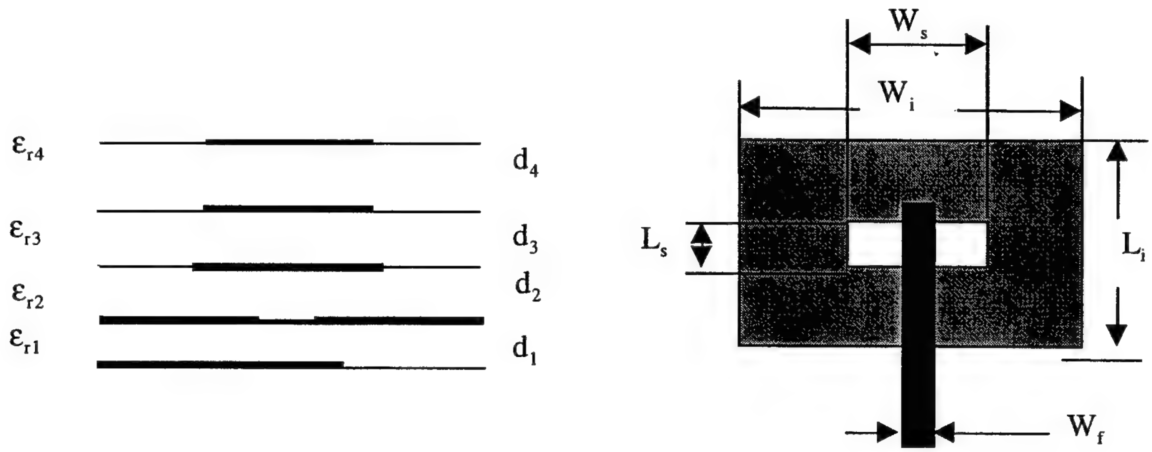


Fig. 7: Side view and top view of an aperture fed Yagi-like antenna

detailed parametric study, using Ensemble, was performed to optimize the location and the size of the slot, the location of the microstrip feed-line and the length of the first patch in the second layer. The final designed antenna dimensions are: W_f=0.033λ_0, W_1=0.494λ_0,W_2=0.498λ_0, W_3=0.451λ_0 ; L_1=0.277λ_0, L_2=0.276λ_0, L_3=0.204λ_0; W_s=0.167λ_0, L_s=0.033λ_0. As can be seen in Figure 8, the design results in a gain of better than 12 dBi and a return loss of less than –15dB at a resonant frequency of 10 GHz,. It is noteworthy that it would be possible to obtain a better match and perhaps a higher gain if a global optimization of dimensions, instead of a parametric study, had been applied. Presently, however, our electromagnetic optimization engine, is not capable of such optimization for structures that include apertures in their geometry.

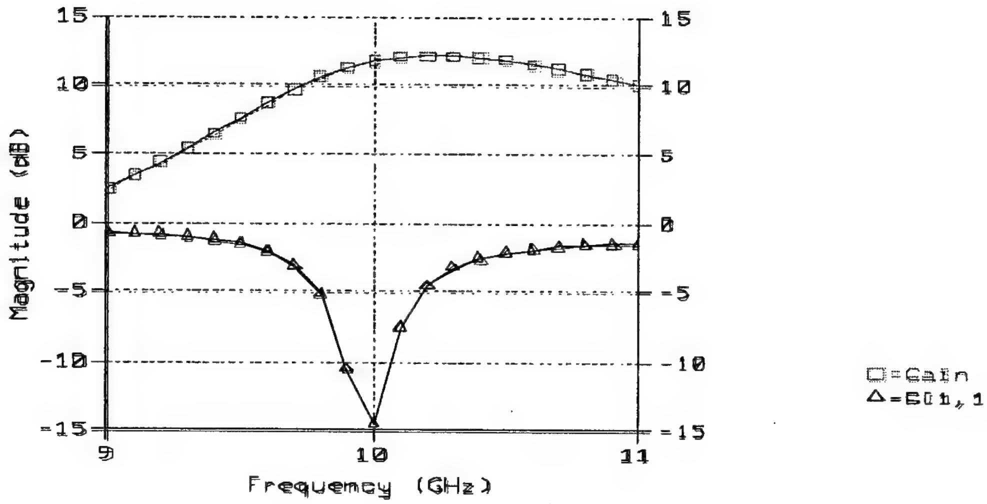


Fig. 8: Gain and return loss of the aperture fed Yagi-like antenna

IV. PERFORMANCE ANALYSES OF LINEAR ARRAYS OF YAGI-LIKE STACKED PATCH SUB-ARRAY ANTENNAS WITH VARIOUS FEEDING TECHNIQUES

A. Performance of Linear Arrays of Yagi-Like Stacked Patch Sub-Arrays

We now examine the performance of the three optimized structures of section II when they are used to form a 2-element as well as a 5-element linear array. It is theoretically reasonable to form an array of such high gain antenna elements for even higher gain, low side lobe and/or steered-beam applications. But since these elements have relatively thick dielectric layers, propagation of surface-waves and strong mutual couplings will adversely affect the gain, axial ratio and input impedance of these antennas.

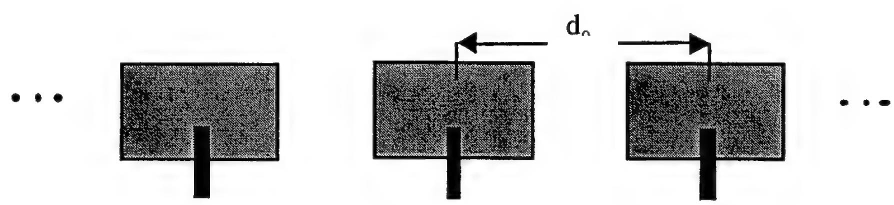
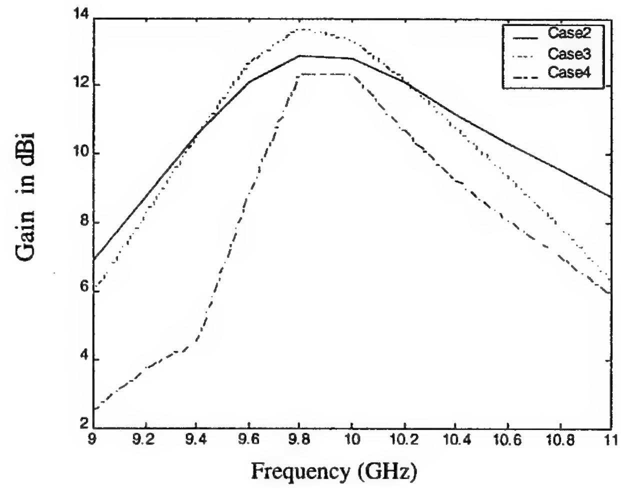


Fig. 9: A linear array of Yagi-like sub-array elements

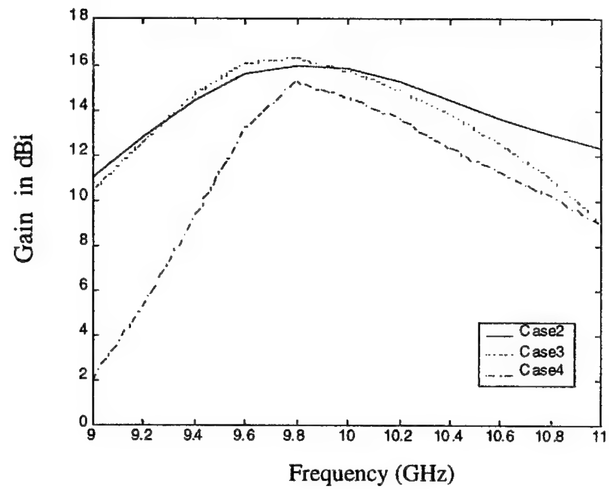
We have investigated the linear array arrangement of Figure 9 where the radiating edges are along the array axis. The array axis is assumed to be along the x-axis with an inter-element spacing of d_0=0.5λ_o. The Gain of a 2-element and a 5-element array as a function of frequency are shown in Figure 9 and Figure 10, respectively. Ignoring the mutual coupling effects, one approximately expects a 3 dBi and a 7 dBi increase over the gain of a single element. As can be seen, however, the

arraying effect adds on the average of only about 1 dBi and 4 dBi for two and five element arrays, respectively. Far-field patterns are plotted in Figure 11 where the plots labeled cases 2, 3 and 4 correspond to one of the three optimized structures with different feeding schemes discussed in section II. The elements in the plot labeled Case 1 are similar to direct microstrip feeding in case 2 but with $L_2 = L_3$. For the latter case the far-field computed when the couplings are neglected (i.e., element pattern multiply by array factor) is also included for comparison.

The results for the gain clearly show that to fully take advantage of the Yagi-like gain enhancement technique, one should globally optimize gain of the whole array, in the presence of the mutual coupling effects, rather than an element in isolation. In the next section, we show that such global optimization can substantially improve the gain of the Yagi-like arrays.



Figures 9: Gain of array of 2 Yagi-like elements; solid: directly-fed; dash: proximity-fed; dash-dot: aperture-fed



Figures 10: Gain of array of 5 Yagi-like elements; solid: directly-fed; dash: proximity-fed; dash-dot: aperture-fed

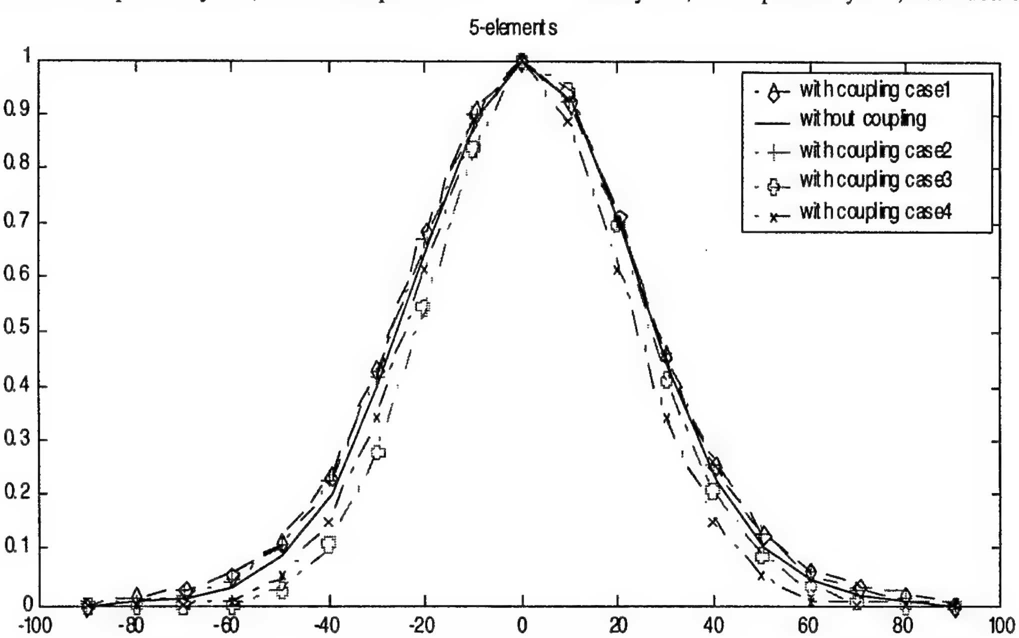
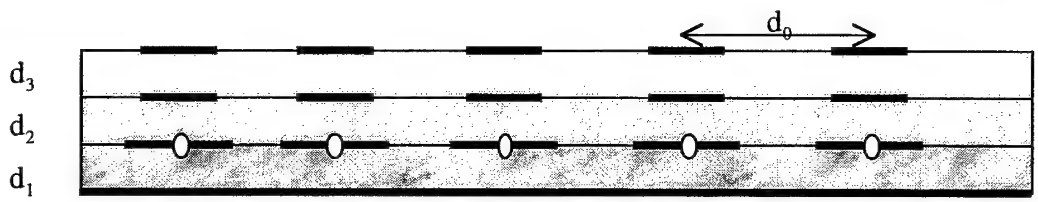


Fig. 11: Far-field pattern of an array of five Yagi-like sub-arrays.

B. Global Optimization of Yagi-like Printed Dipole Arrays

In our last annual technical report, we examined the performance of a linear array of Yagi-like sub-arrays of strip dipole elements center-fed by a voltage generator. An examination of the expected gain and the degradation in pattern indicated that the surface-wave reduction mechanism, resulted from optimization of the lengths of the sub-array elements and the thickness of the dielectric layers, had been disturbed by the mutual coupling effects. Therefore to enhance the gain for these Yagi-like structures one should globally optimize gain of the whole array, in the presence of the mutual coupling effects, rather than an element in isolation. To demonstrate the feasibility of such optimization we have selected one of the structures studied in [2], which has the narrowest bandwidth and is more susceptible to mutual coupling and surface-wave effects. The parameters for optimization include the lengths, L_1, L_2 and L_3, of printed strips, varied in the range of $[0.2, 0.5]\lambda_0$, and thickness of layer 2 and layer 3, varied in the range of $[0.1, 0.5]\lambda_d$. The gain was then optimized with the EP population size of $\mu = 10$ and number of opponent of $q = 4$. Final optimized Gains for 2-element and 5-element collinear array were achieved within 200 generations. The final optimized gain and design parameters for 2-element and 5-element Yagi-like antenna arrays, obtained within 200 EP generations, are given in Table 3. The corresponding parameters before the global optimization [2] are included for comparison. These results show an average of 1dBi improvement in the array gain after the global optimization, which included the coupling effects.



Inter-element spacing $d_0 = 0.5\ \lambda_{d1}$	Gain (dB)	d_1 (λ_{d1})	d_2 (λ_{d2})	d_3 (λ_{d3})	L_1 (λ_{d0})	L_2 (λ_{d0})	L_3 (λ_{d0})
1-element	13.57	0.240	0.120	0.360	0.318	0.3295	0.3889
2-element collinear array before Global optimization	14.41	0.240	0.120	0.360	0.318	0.3295	0.3889
2-element collinear array after Global Optimization	15.44	0.270	0.163	0.227	0.358	0.327	0.490
5-element collinear array before Global optimization	16.07	0.240	0.120	0.360	0.318	0.3295	0.3889
2-element collinear array after Global Optimization	17.01	0.159	0.194	0.311	0.391	0.327	0.401

Table 3: Global optimization of a 2- and a 5-elemnt Yagi-like array of printed dipoles

V. HIGH GAIN MICROSTRIP PATCH ANTENNAS WITH A HIGH PERMITTIVITY FOCUSSING LAYER

In the last progress report we investigated a gain enhancement method based on the resonance condition of a single microstrip patch in multilayer geometry with a high permittivity focusing superstrate layer. In particular, we demonstrated the feasibility of the method in design of a circularly polarized probe-fed nearly square microstrip antenna for MSAT operation at 1.6 GHz. Coaxial feeding technique, however, is not suitable for printed array applications and feasibility of other feeding techniques in conjunction with this gain enhancement method should be investigated. In the following we report our work on proximity and aperture feeding schemes with applications to design of high gain antennas with linear, circular or dual polarization. It is important to note that the total thickness (~0.55 λ_0) of the structures analyzed here may be impractical for lower microwave frequency ranges. Extension of the concepts into millimeter-wave region, however, is straight forward and should result in low profile high gain radiating elements that would be attractive for many wireless applications such as in LMDS wireless system that operates at 27 GHz and higher.

A. Proximity-fed Microstrip Antenna with Linear Polarization

In the proximity-fed configuration a microstrip line on the first layer electromagnetically feeds a rectangular patch on top of the second layer. The patch is covered with two superstrate layers with low and high dielectric constants as shown in Figure 12. In the example presented here, parameters

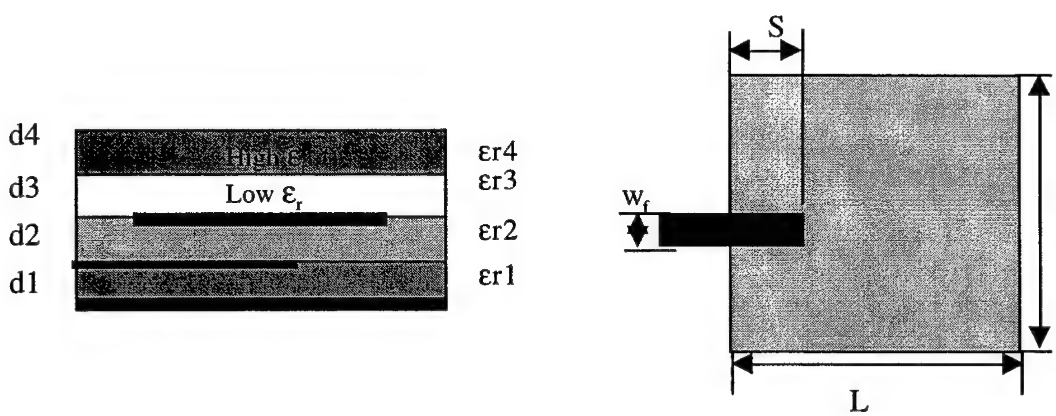


Fig. 12: The side view and the top view of the proximity-fed antenna for linear polarization

of the first two layers were assumed to be $\varepsilon_{r1} = \varepsilon_{r2} = 2.2$, d_1=1.0875mm and d_2=0.5mm. Using the MOM-based simulation code, Enemble, patch dimensions, L and W, and feed inset position, s, were initially adjusted, in the absence of any superstrate layer, until a low return loss was achieved at the

design frequency of 1.643 GHz. The realized gain, however, was only about 7 dBi. Next, in order to enhance the gain, a high permittivity focusing layer (ε_{r4} = 10.5) of thickness d_4 is added at a distance of d_3 from the patch surface as shown in Figure 12. A high gain operation can now be achieved by adjusting the thickness d_3 when d_4 is fixed according to the resonance condition [9]: $d_3 = \lambda_0 / 4\sqrt{\varepsilon_{r3}}$. It is noteworthy that the presence of the air layer (i.e., ε_{r3}=1.0) allows an easy mechanical tuning of d_3 in a practical design [10]. Resonance frequency of the original patch shifts, however, when the high permittivity layer is added which hence requires adjustments of the patch dimensions and the feed position. For this purpose, we need to slightly tune the thickness of d_3 and the length and width of the patch until a good VSWR and high gain at the desired frequency are achieved at the same time. Final design results has a broadside gain of nearly 12 dBi with S_{11} = -26dB (i.e.., VSWR = 1.1) at f=1.643 GHz. The parameters of the final 4-layer structure are, d_3=77 mm, d_4=24.5 mm, L=59.7 mm, W=60.52 mm s =10.4 mm and w_f=4.0mm where w_f is the width of microstrip feed line.

B. Proximity-fed Microstrip Antenna with Dual Polarization

A dual linearly polarized antenna is desirable for applications that demand frequency reuse or simultaneous transmit and receive operations. Dual polarization is particularly important for enhancing system capacity and signal to noise ratio in emerging wireless and millimeter wave communications where polarization diversity is used as an effective way of reducing the multipath and other signal fading effects. Two widely used feeding schemes for dual polarization in microstrip antennas are proximity-coupled and aperture-coupled feeding techniques. Here we concentrate on the former technique whereas the integration of the latter feeding scheme with the focusing-layer gain enhancement technique will be presented in subsection C.

Geometry of the proximity-fed antenna for dual polarization is shown in Figure 13. A nearly square patch is proximity coupled to a pair of perpendicular microstrip feed lines located on the

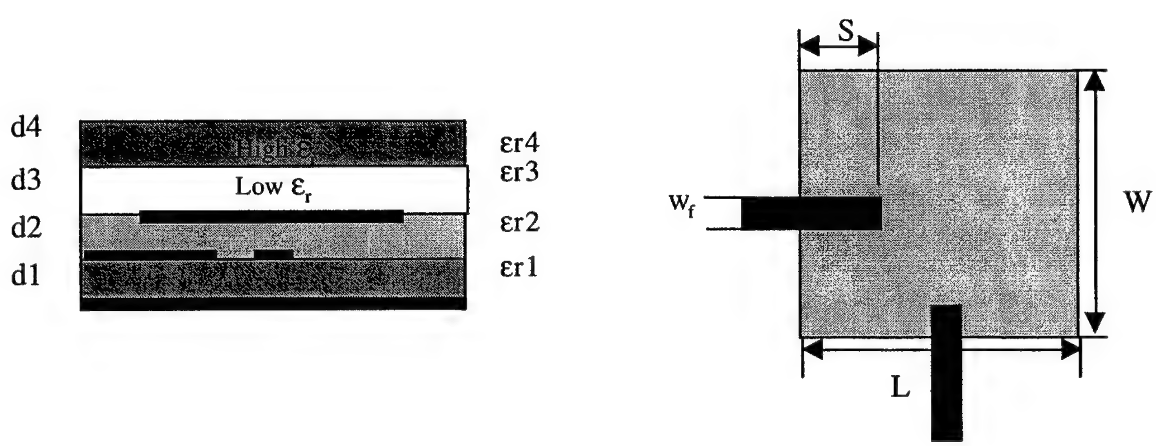


Fig. 13: The side and the top views of the proximity-fed antenna for dual polarization

first substrate layer. In order to achieve the dual linear polarization as well as high gain and good return loss, we need to optimize the dimensions of the structure such as the length and width of the patch, and the offsets and insets of the two orthogonal feed lines. Using ENSEMBLE, our design procedure is as follows: First the width of the patch is selected according to equation (3), then the offset and inset of one of the feed lines are adjusted while keeping the other feed line right at the center of the patch. Position of the second feed line is adjusted after the first feed line is designed for good return loss and dual polarization. The width to length ratio of the patch should then be slightly modified to maintain required resonant frequency. To achieve the desired high gain, the high-permittivity focussing layer and the air layer are then added to this designed structure. Again, we have to adjust the thickness of two new layers while maintaining good return loss, high gain and dual polarization at the same time. To that end we may need to tune the dimensions of the existing structure slightly.

An example of a designed structure for operation at f = 1.643 GHz includes the following parameters: ε_{r1}=10.5, ε_{r2}=2.2, ε_{r3}=1.0, ε_{r4}=10.5, d_1=1.0875mm d_2=0.5mm, d_3=77mm, d_4=24.5mm, s=24.6mm, w_f=2.0mm, L=57.5mm and W=60.52 mm. The return loss and the matched gain versus frequency are plotted in Figure 14. As seen, this four-layer geometry, results in a gain of 11.5dBi

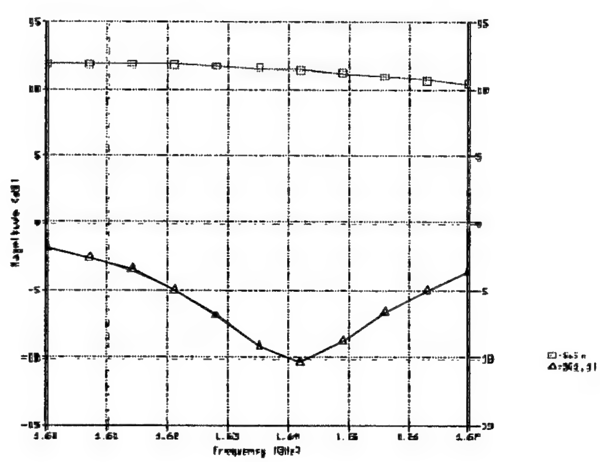


Fig. 14 Gain and return loss of a dual-polarized microstrip antenna with a high permittivity focussing layer

with a return loss of S_{11} = -10.5dB. The corresponding E_θ and E_ϕ far-field patterns in Figures 15 clearly show the dual-polarized operation at broadside The patterns when the structure is excied by

only one feed-line is also shown for comparison. The latter shows a polarization isolation of about 50 dB. It should be noted that design of this antenna can be greatly improved if we apply a global evolutionary optimization of all of the parameters instead of the step by step adjustments of these parameters as was detailed above.

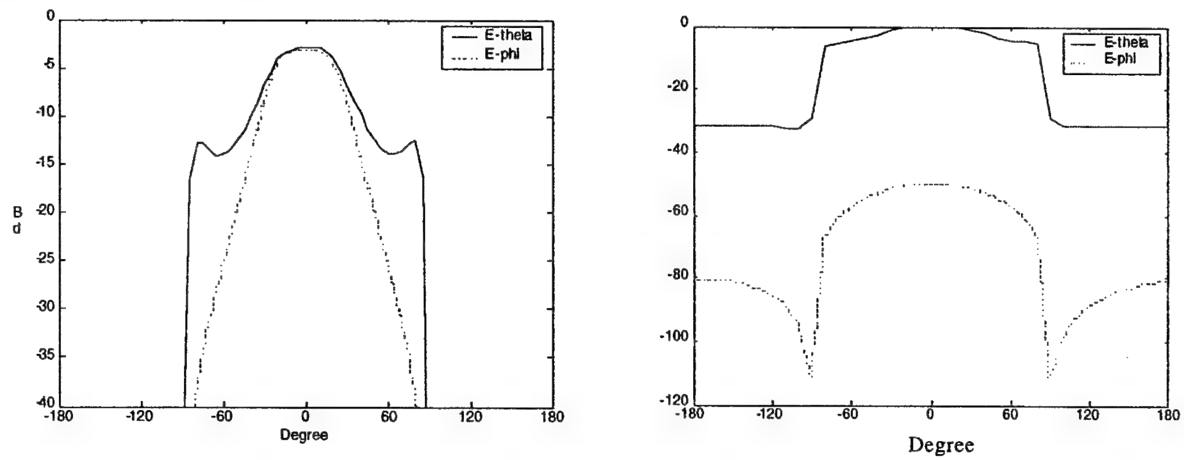


Fig. 15: Far-fields of dual-polarized microstrip antenna with a high permittivity focussing layer; Righ-hand plot shows the patterns when the structure is excited by only one feed-line

C. Aperture-fed Microstrip Antennas with Single and Dual Polarization

Figure 16 shows a linearly polarized aperture-fed microstrip antenna with a focussing high ε_r layer. The antenna is composed of 4 dielectric layers: the feeding line substrate, a patch supporting substrate, air layer and the high ε_r layer. A ground plane between the layers 1 and 2 isolates the radiator from the microstrip feed circuitry. Slot in this ground is used to electromagnetically couple signal from the microstrip line to the radiating patch antenna. To demonstrate the capability of this structure as a high gain radiator, we have designed and analyzed an antenna at f = 1.643 GHz. The dielectric constants and thickness of the layers were, ε_{r1} =10.5, ε_{r2} = 2.2, ε_{r3} = 1, ε_{r4} = 10.5, d_1=d_2=0.794mm d_3=77.0mm and d_4=24.5mm. The patch and microstrip line parameters were: L=60.4mm, W=61.9mm, Ls = 20.0mm, w_d=5mm, w_f=4.0mm and w_o=10.2mm. This configuration results in a gain of about 11.7 dBi.

We have also investigated a dual polarized version of this high gain structure, shown in Figure 17. The two slots in this structure are placed under the patch in an "L" configuration. A preliminary analysis of this structure has shown that a gain of better than 11dBi with a good polarization isolation can be achieved.

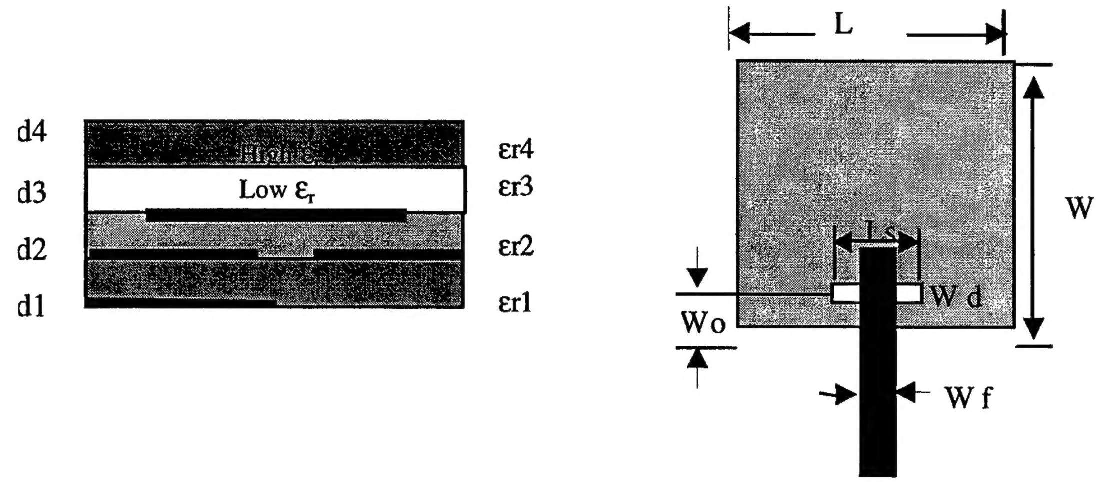


Fig. 16: The side and the top views of the aperture-fed antenna for linear polarization

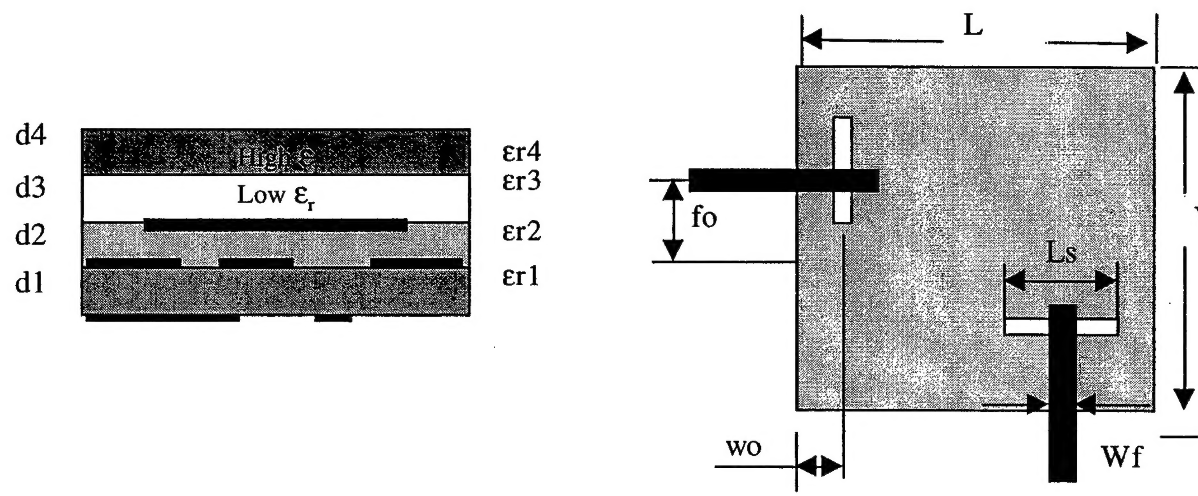


Fig. 17: The side and the top views of the aperture-fed antenna for Dual polarization

D. Aperture-fed Microstrip Antenna with Circular Polarization

In an aperture-fed high gain microstrip antenna with CP operation, we need to optimize not only the dimensions of the patch, and position, width, and length of the slot but also the orientation, θ, of the slot as shown in the Figure 18. We have used a nearly square patch with dimensions L and W, where W was initially selected according to equation (3). The dimensions and orientation of

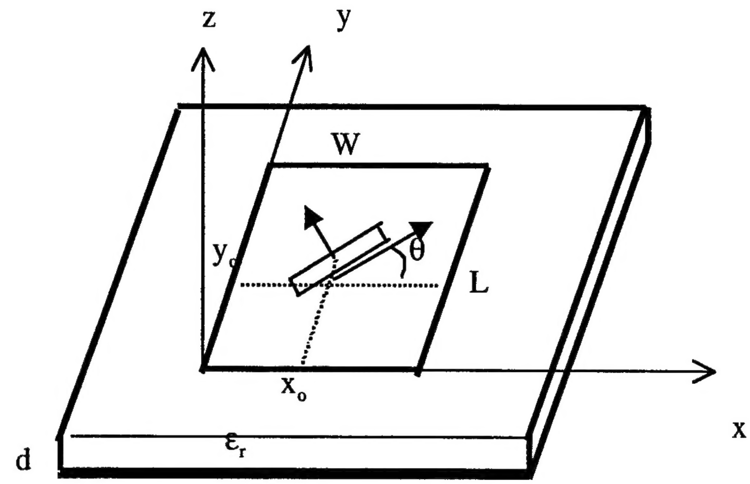


Figure 18: Geometry of a rectangular microdtrip antenna with an arbitrary oriented slot feed

the slot were also initially approximated according the procedure given in [11]. Using a MOM-based simulation code, the dimensions of the patch and the slot were first optimized, in the absence of any superstrate layer. The high permittivity focussing layer and the air layer are then added and their thickness adjusted according to the procedure described in sections A and B above. Final design in Figure 19 has resulted in a gain of about 11 dBi with an axial ratio of AR = 3.5 dB and a return loss of S_{11}= -18 dB at f=1.643 GHz. The design parameters for this antenna structure were: ε_{r1}= 10.5, ε_{r2}= 2.2, ε_{r3}=1.0, ε_{r4}= 10.5 d_1 = d_2 = 0.79375mm, d_3=77.0mm d_4=24.5mm, L=59.8mm, W=61.4mm, Ls = 15.0 mm, W_d = 3.0 mm and θ =1.5°. Design of this antenna, particularly the axial ratio, can be improved if we apply a global evolutionary optimization of all of the parameters instead of the step by step adjustments of these parameters.

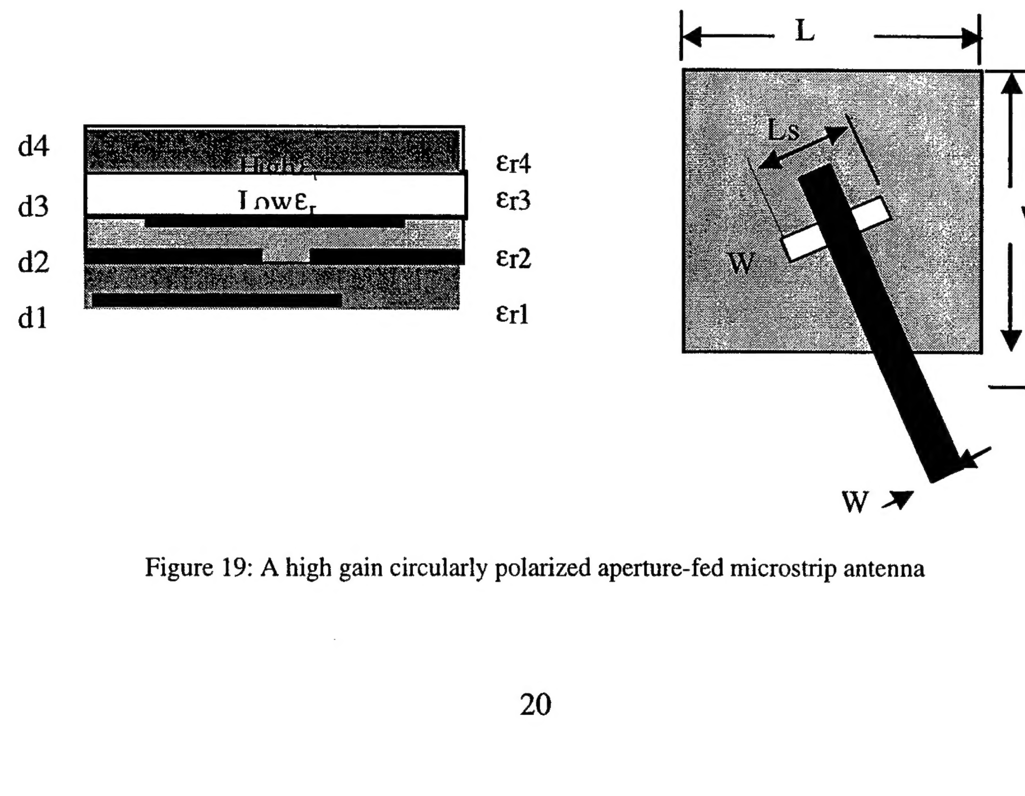


Figure 19: A high gain circularly polarized aperture-fed microstrip antenna

REFERENCES

[1] A. Hoorfar, "Investigation of a new class of multi-layered printed antennas for applications in communications and radar," *Annual Report submitted to ONR*, October 1998.

[2] A. Hoorfar, "Investigation of a new class of multi-layered printed antennas for applications in communications and radar," *Annual Report submitted to ONR*, October 1999.

[3] A. Hoorfar, "Mutation-based evolutionary algorithms and their applications to optimization of antennas in layered media," *IEEE AP-S International Symposium*, Orlando, FL, July 1999.

[4] C, A. Balanis, Antenna Theory, Analysis and Design, *Wiley & Sons Inc.*, 2nd edition, 1997.

[5] ENSEMBLE™, *Ansoft Corporation*, 1998.

[6] D. M. Pozar, "Microstrip antennas", *Proc.IEEE*, 1992,80,pp.79-91.

[7] Zurcher, J.F.and Gardiol,F.E. Broadband Patch Antennas. Norwood 1995, *Artech House*, Inc., 209p.

[8] F. Croq and Pozar, D.M. "Millimeter-wave design of wide-band aperture-coupled stacked microstrip antennas." *IEEE Transactions on Antennas and Propagation*. 39(1991) 12,pp.1770-1776.

[9] D. R. Jackson and N. G. Alexopoulos, "Gain enhancement methods for printed circuit antennas", *IEEE Trans. Antennas Propagat.*, Vol. AP-33, pp. 976-987, Sept. 1985.

[10] X. H. Shen and A. E. Vandenbosch, "Study of gain enhancement method for microstrip antennas using moment method," *IEEE Trans. Antennas Propagat.*, Vol. AP-43, pp. 227-231, March 1995.

[11] M.I.Aksum, S.L. Chuang, andY.T.Lo, "Theory and experiement of electromagnetically excited microstrip antennas for circular polarization operation, " *IEEE Antennas Propagat. Soc. Symp.*, San Jose, CA, June 26-30, 1989.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 30, 2000	Interim: October 1, 1999 – September 30, 2000

4. TITLE AND SUBTITLE

INVESTIGATION OF A NEW CLASS OF LOW-PROFILE MULTI-LAYER PRINTED ANTENNAS

5. FUNDING NUMBERS

G - N00014-98-1-0090

6. AUTHOR(S)

Ahmad Hoorfar

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

Villanova University
800 Lancaster Ave.
Villanova, PA 19085

8. PERFORMING ORGANIZATION REPORT NUMBER

Acc: 527615

9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Center Tower One
800 North Quincy Street
Arlington VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release: distribution is unlimited

12. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This progress report outlines our research efforts on modeling, analyses and optimization of multi-layered printed antennas for high gain applications. Our research during this interim period has resulted in progress in the following areas. 1) The Yagi-like high gain concept has been extended to the practical cases of microstrip-fed, proximity-fed and aperture-fed array of rectangular patches. For each case a 3-layer Yagi-like antenna is optimally designed at a frequency of 10 GHz. Performance of each antenna in terms of its gain, return loss and input impedance versus frequency is investigated. It shown that a gain of about 12 dBi or higher can be obtained in each feeding scheme. In addition, for each case we have investigated the coupling effects between two or more these Yagi-like sub-arrays in order to assess their performance in a linear array application. 2) A gain enhancement method under investigation in this project has been based on the resonance condition of a single microstrip patch in a multilayer geometry with a high permittivity focusing superstrate layer. We have now extended this high gain technique to design of proximity-fed and aperture-fed antennas for applications that require linear, circular or dual polarization (i.e., polarization diversity antennas). 3) We have extended our method of moment code to include Yagi-like stacked patch antennas printed in a multi-layer anisotropic medium. Integration of this code with our evolutionary optimization engine is currently in progress. 4) We are currently in the midst of developing a numerical code, based on the finite-difference time-domain (FDTD) method, for radiation as well as RCS analysis of the multi-layer printed Yagi-like antennas on cylindrical surfaces.

14. SUBJECT TERMS

Printed Yagi-Like arrays, Multi-Layered Microstrip Antennas, Method of Moments, Gain Optimization, Evolutionary Programming

15. NUMBER OF PAGES

22

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	